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X-ray Astronomical Polarimetry in the XEUS Era

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Abstract. X-ray Polarimetry is almost as old as X-ray Astronomy. Since the first discovery of X-ray sources theoretical analysis suggested that a high degree of linear polarization could be expected due either to the, extremely non thermal, emission mechanism or to the transfer of radiation in highly asymmetric systems. The actual implementation of this subtopic was, conversely, relatively deceiving. This is mainly due to the limitation of the conventional techniques based on the Bragg diffraction at 45^o, or on Thomson scattering around 90^o. Acually no X-ray Polarimeter has been launched since 25 years. Nevertheless the expectations from such measurement on several astrophysical targets including High and Low Mass X-Ray Binaries, isolated neutron Stars, Galactic and Extragalactic Black Holes is extremely attractive. We developed a new technique to measure the linear polarization of X-ray sources. It is based on the visualization of photoelectron tracks in a, finely subdivided, gas filled detector (micropattern). The initial direction of the photoelectron is derived and from the angular distribution of the tracks the amount and angle of polarization is computed. This technique can find an optimal exploitation in the focus of XEUS-1. Even in a very conservative configuration (basically the already existing prototype) the photoelectric polarimeter could perform polarimetry at % level on many AGNs. Further significant improvements can be expected from a technological development on the detector and with the use of XEUS-2 telescope.

1. Introduction

Historically we can group the measurements performed on Astronomical X-ray Sources into four groups:

- Timing Photometry (Geiger, Proportional Counters, MCP) with Rockets, UHURU, Einstein, EXOSAT, ASCA, SAX, XMM, Chandra.
- Imaging:
  Pseudo-imaging (modulation collimators, coded masks), SAS-3, XTE-ASM, SAX-WFC, HETE-2
  Real Imaging (grazing incidence optics + Position Sensitive Detectors: IPC, MCA, CCD) with Rockets, Einstein, EXOSAT, ROSAT, ASCA, SAX, Chandra, Newton.
- Spectroscopy:
  Non dispersive (Proportional Counters, Si/Ge and CCD) Rockets, Einstein, EXOSAT, HEAO-3, ASCA, SAX, Chandra, Newton.
  Dispersive: (Bragg, Gratings) Einstein, Chandra, Newton
- Polarimetry (Bragg, Thomson/Compton) with rockets Ariel-5, OSO-8

While in the domain of Photometry, Imaging and Spectroscopy the observing techniques have been tremendously improved, Polarimetry has only been based on the same, conventional techniques, producing important but very limited results. In fact, after OSO-8, no astronomical Polarimeter has been flown any more.

2. Why X-ray Astrophysical Polarimetry?

Polarization from celestial sources may derive from:

- Emission processes themselves: cyclotron, synchrotron, non-thermal bremmstrahlung (Westfold, 1959; Gnedin & Sunyaev, 1974; Rees, 1975)

- Scattering on aspherical accreting plasmas: disks, blobs, columns (Rees, 1975; Sunyaev & Titarchuk, 1985; *Mézáros* et al. 1988).
- Resonant scattering of lines in hot plasmas (Sazonov 2002).
- Vacuum polarization and birefringence through extreme magnetic fields (Gnedin et al., 1978; Ventura, 1979; *Mézáros* & Ventura, 1979)

3. Polarization expected in X-ray Pulsators

The role that polarimetry can play in these sources is straightforward. We know that the emission mechanisms and we know, because we directly measure, the rotation period of the neutron star (from the light curve) and, in some cases, the intensity of the magnetic field (from cyclotron lines), and the masses (or at least the mass ratio) from optical spectroscopy and possibly from doppler effect on the X-ray period. But other important parameters such as the inclination of the magnetic to the mechanical axis or the inclination of the rotation axis on orbit plane are free parameters to be derived from fitting data of spectral variability. So far we do not know whether or when the emission is in the form of a fan or of a pencil. As computed in detail by *Mézáros* et al. (1988) the polarization of the cyclotron emission and the different scattering cross section produces a high degree of linear polarization strongly variable with energy and phase. With a pencil beam the degree of polarization will be anticorrelated with the luminosity, while for a fan beam it will be correlated. We will actually *see* the magnetic axis swinging around the rotation axis projected on the sky. All the geometry of the system will be completely frozen.

4. Polarization expected in isolated Neutron Stars

Radiation can be polarized when crossing an extreme magnetic field for the birifringence. Soft thermal X-ray radiation is produced by a NS atmosphere at T_{eff} of 0.3 to 3 x 10^6 K. The opacity of a magnetized plasma depends on polarization. While the effects of magnetic field on the spectrum are negligible the effects on polarization are outstanding. The degree of polarization (10%-30 %) depends on photon energy, Teff, magnetic field and mass-to-radius ratio. Pavlov & Zavlin, 2000. In radio pulsars with thermal X-ray emission, phase resolved polarimetry,will provide mapping the magnetic field. Even more dramatic effects are expected in Soft Gamma Repeaters, in the frame of the magnetar model.

5. Polarization from Scattering in Accretion Disks and General Relativity effects

Intrinsically unpolarized radiation can be polarized by scattering as well, provided that scattering angles to the observer are selected by the system geometry. Chandrasekhar (1960) computed the maximum polarization (17%)that can derive from an infinitely extended, infinitely thin scattering cloud. In accretion disks around compact objects photons are Compton scattered by high energy electrons have an energy substantially different from parent population. Therefore in the X ray range the radiatin can be highly polarized either in the direction perpendicular to the major axis of the disk or in that parallel (Lightman & Shapiro, 1976, Sunyaev & Titarchuk, 1985).

The polarization properties are altered by gravitational effects. The polarization plane rotates continuously with energy because of light bending predicted by General Relativistic effects combined with the radial temperature distribution in the disk. This is a signature of the presence of a black-hole (Stak& Connors, Connors& Stark, 1977, Connors, Piran & Stark, 1980).

6. Polarization of AGNs

In Seyfert Galaxies and QSOs the effects of scattering, kinematics and GR are all combined. Moreover the disk/torus geometry produces significant selection effects in the scattering angles. Also, in condition of high accretion rate, the X-ray illuminated disk can be altered in its ionization and temperature structure producing polarized radiation at energies of 2-6 keV (Matt, Fabian & Ross, 1995).

Blazar emission will be synchrotron at lower energies and is expected to be highely polarized (as in IR). At higher energies inverse compton will prevail and the degree of polarization should decrease and the angle rotate. From the energy resolved polarimetry the geometry and energy distribution of the electrons within the jet can be studied (Poutanen, 1994).

7. Miscellaneous Targets

- Non thermal X-ray emission from pulsars (for Crab P $<$ 8%)

– Pulsations in LMXB (QPOs and millisecond pulsar)
– Edge-on X-ray binaries (polarized lines?)
– Jets in Galactic Miniquasars (synchrotron?)
– Non thermal components in thermal Supernova Remnants (local or extended)
– Non thermal component in Galaxy Clusters
– Gamma-Ray Burst Afterglows
– Solar Flares

8. Conventional Techniques

Compared with great expectations of the theoretical analysis, the experimental results are quite meagre. In the beginning of X-ray astronomy polarimeters were flown aboard rockets, and satellites ARIEL-5 and OSO-7. In practice the only positive result was the detection of polarization by Crab Nebula by the team of Columbia University, with a rocket and with OSO-8: 19.2 % at 2.6 keV (Weisskopf et al., 1978).

This is mainly due to the limitations of the conventional techniques of Bragg diffraction and Compton scattering. A Bragg crystal, operated at 45^o, and rotated around the optical axis, is an excellent analyzer of Polarization. It preserve imaging but the efficiency is very poor. Compton around 90^o is a good compromise of efficiency and modulation, but, unless the energy lost in the scattering is measured (what is typically possible at higher energies only), completely destroys positional information and results in set-up huge, with high background and very serious systematic effects, that are partially removed by rotating the whole set-up. The best implementation of these two techniques is the Stellar X-Ray Polarimeter (Kaaret et al. 1990), made for the SPECTRUM-X-Gamma Mission, so far not flown.

9. Photoelectric Polarimetry

The distribution of electrons in photoelectric effect is good analyzer of polarization, almost at the same level of Bragg diffraction, but involves a large slice of the X-Ray spectrum. When the photon is absorbed by the inner shells of an atom, a photoelectron is ejected with a kinetic energy which is the difference of the photon energy and the binding energy of the electron. The photoelectron is preferentially ejected (actually with a cos^2 distribution) on a plane perpendicular to the incoming photon. Within this plane the ejection directions are peaked around the electric field of the photon (again with a cos^2 distribution).

The photoelectron interacts with the matter around the initial atom by several processes, two of which are almost exclusively determining its kinematics: it is slowed by ionizing collisions with atomic electrons and scattered by coulomb diffusion on the charge of the nuclei. The photoelectron, just like any electron of any other origin, leaves in the absorber a track, namely a string of electron/ion pairs, topologically connected, marking the path from the creation to the stopping point. All this Physics was studied in detail by Auger in 1926 by means of a cloud chamber filled with various mixtures of gas. The tracks of the photoelectrons, created along the X-ray beam path, are visualized by the cloud chambers as chains of bright dots. Incidentally by studying the images Auger discovered the presence of an additional electron of fixed energy produced by the self-ionization of the excited ion, since then named the Auger Electron. The cloud chamber, thanks to the low density of the conversion/detection material, is an ideal tool to microscopically resolve the photoelectron track. But a clod chamber is definitely a ground based device.

Many workers tried in the past to design sensitive x-ray polarimeters based on the photoelectric effect but with scarce or no success. Some are based on a combination of a solid photo-cathode and an electronic detector and they require very high grazing incidence and pointing stability, while they do not provide energy information on the X-ray flux. Other attempt, with a single integrated analyser and detector, were frustrated. Actually they detected polarisation only as an 'edge' effect, either by counting coincidence in neighbors proportional counters wires (Riegler G.R. et al. Bull. Am. Phys. Soc., 15, 1970, 635.) or in neighbors CCD pixels (Tsunemi et al., NIM, 1992). Only with the advent of finely segmented gas detectors it now possible to detect polarization, with the highest sensitivity, in the canonical energy band for X-ray Astronomy. This approach has been attempted by means of gas luminescent detectors read with a CCD through an imaging optics (Austin 1993, La Monaca 1998, Sakurai 2001), but the capability to efficiently apply this method to low energ X-rays is still to be verified. In the following we present a newly developed detector, already available for a space experiment.

10. A new device: the MICROPATTERN DETECTOR

Position sensitive gas detectors, such as the Multi-Wire Proportional Chamber, typically come out with a single information on a X-ray event such as the center of gravity or the cross-over time. This information includes all data

Fig. 1. Design of the Micropattern detector with GEM and readout plane with exagonal pads

Fig. 2. Detector plane with exagonal pads currently working as laboratory prototype

Fig. 3. Close-up view of the hexagonal pads as readout plane of the laboratory prototype

Fig. 4. Photoelectron tracks produced in gas in the laboratory prototype by 5.4 keV photons

on the photoelectron track. In this sense the extension of the track is usually considered as a *noise*, something to be kept as small as possible in the design. For the Multi-Wire Proportional Counter the extension of the track is considered the ultimate limit to the space resolution. Our approach is orthogonal. We image the track to reconstruct the interaction point and the prime direction of the photoelectron: something very similar to the cloud chamber but including electronic read-out, measurement of the deposited energy, self trigger capability, moderate encumbrance .

This modern Cloud Chamber is the Micropattern Gas Chamber (Costa, Bellazzini et al., Nature 2001). It consists (fig. 1, fig.2) of a gas cell with a drift region, a multiplication stage (actually a Gas Electron Multiplier) and a multi pixel true bi-dimensional read-out anode. We have constructed a multi-pixel hexagonal read-out built on an many-layer PCB (fig.3). The high granularity allows the tracks of individual photoelectrons emitted by each incident X-ray to be followed. The device combines almost the best performances of gas detectors: pixel sizes from 50 to 200 μm are feasible, the signal is very fast(tens of ns), and the energy resolution reasonable, close to the optimum for such devices (10% at 6 keV). Each pixel is connected to a pre-amplifier and ADC channel which allow to detect the energy lost in that pixel. The images of the tracks contain therefore also the information of the dynamics of the photoelectron energy loss and of the energy of the primary photon. By taking the signal from the GEM we trigger the acquisition of the anode signal and perform an optimal pulse height analysis. We collect a track for each detected photon (see fig 4).

The actual track is made as a skein and from its analysis is always possible to identify the 'head' which carries most of the information on the polarization from the tail which does not. We collected tracks from a very finely collimated 5.4 keV unpolarized sources. The loci of the centroids of each track are located on a circular region around the interaction points indicating the tracks, even at this low energy, are not randomized (fig.5). From each track we reconstructed the emission angle. The histogram of the emission angles is indicative of the presence of polarization in the incoming X-ray photons. In case of non polarised X-ray photons, such as fluorescence lines, all the emission angles have the same probability and the histogram is, therefore, a flat curve. We measured a flat curve from the fluorescence line produced by an Fe^{55} source at 5.9 keV or Chromium lines at 5.4 keV indicating that no major spurious effects were present (fig. 6.1). We, instead measured a significative deviation from a flat curve when we shined the detector with a polarized X-ray source of 5.4 keV (fig.6.2).

This data are well modelled, also quantitatively, with what we expect if we take into account the theoretical distribution of the photoelectron and the smearing effect due to the scattering and to the lateral diffusion of electrons in the drift from the absorption point to the GEM.

Therefore we built a detector with combined Polarimetric, Imaging, Spectral and Timing capabilities and master the simulation tools to design different configurations dedicated to a particular experiment set-up.

11. A MICROPATTERN detector in the focus of XEUS-1.

In order to evaluate the capabilities of such a device in the focus ox XEUS we follow a very conservative approach. We assume to build a detector with the main features of an existing prototype, extended to include the whole XEUS PSF. We compute the expected counting rates from sources and from background (from literature data) and the modulation factor from monte.carlo simulations confirmed from our prototype measurements. This can be mounted within a conventional set-up for gas counters such as the BeppoSAX MECS GSPC, with a ceramic body and a thin (50μm) Beryllium window . This is far from an optimal device but is something of which we can guarantee, since

Fig. 5. Locations of the Baricentres for 5.4 keV polarized photons as derived by the tracks detected by the Micropattern

Fig. 6. Modulation curve measured with an unpolarized source Fe^{55} (left panel) and a polarized 5.4 keV source (right panel)

Table 1. MDP for AGNs in 10^5 s in the 2-10 keV energy band with XEUS-1

AGNs	MDP%
CENA	0.6
NGC4151	0.7
NGC5548	0.8
MCG 6-30-15	1.2
Circinus Galaxy	2.8
IC4329A	0.7
Fairall 9	1.6
MKN501 (Outburst)	0.5
MKN421	0.7
3C273	0.9

[a] This is a footnote

Fig. 7. Effective area of two micropattern detector for low-energy (0.1-2 keV) and high-energy (2-10 keV) application at the focus of zero-growth XEUS-1 mirrors. In full colors are represented the energy bands of X-ray polarimetric sensitivity.

now the feasibility, and is capable to perform on a representative sample of celestial objects the large majority of measurements foreseen in the literature, including AGNs.

In Tab.1 we show the Minimum Detectable Polarization for a sample of bright AGNs with a one day observation with such a device in the focus of XEUS-1. Energy resolved Polarimetry in 3-4 bands is possible as well at 1-2 % level on all of them. Of course a much more detailed study is possible on Galactic Sources. We stress the point that in our imaging we can use the reconstructed absorption point (an not the centroid an in a MWPC). This means that we have a (experimentally verified) position resolution of around 100μm, suitable to exploit all the quality of XEUS optics. Therefore XEUS could perform angular resolved polarimetry: e.g. independent polarimetry of an AGN and of its jet; polarimetry of individual knots of a SNR, polarimetry of regions of a cluster suspect to host non-thermal components. Also the system wold have full timing capability and could perform time-resolved polarimetry: e.g. phase and energy resolved polarimetry of binaries and of radiopulsars and SGR. A last point we want to stress is that, as verified at first order with laboratory testing, systematic effects on this polarimeter are well under control and no rotation is needed to remove them (as in a conventional scattering or bragg polarimeter).

12. Improvements with XEUS-1 and XEUS-2

The conservative configuration giving the results in the table is in no way optimal. The efficiency and modulation of the detector can be improved by increasing the absorption gap and modifying the gas filling mixture to reduce the scattering and/or the diffusion on the drift, the two major effects that smear the track. Also the algorithms so far used are relatively simple and can be improved by techniques of pattern recognition.

Another important improvement may be achieved by using instead of one detector, covering the whole energy range, two detectors optimized in two different bands. The complexity increases but the total time to achieve a broad band measurement will be significantly reduced. In fig.7 we show the effective area of our conservative configuration (on the right), effective from 2 to 10 keV, and (on the left) of a low energy detector, optimized in the band 0.6 - 3 keV. Such a low energy device could allow for 1% polarimetry of MK421 in 10^4s.

A further important improvement can derive from the implementation of XEUS-2 optics. From statistics the MDP will scale with the square root of areas. Even though we cannot nowadays be sure of our capability to control systematic effects to perform reliable polarimetry below 1%, the observations will be significantly shorter and the sample will become much richer including AGNs at higher red-shift.

13. Conclusions

We conclude that with the new MICROPATTERN device, the Polarimetry of Astrophysical sources is now feasible, provided that a high throughput optics is used. This will open a new window in the sky and dramatically improve our understanding of Physics of X-ray emitting regions around NS and Black Holes. With XEUS-1 optics, and with moderate assumptions on technological developments, polarimetry to the % level of tens of AGNs will be feasible.

Therefore we think that the inclusion of a MICROPATTERN photoelectric polarimeter in the baseline payload for XEUS-1 should be seriously considered.

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